91602
new 82-10

COMPLIMENTARY COPY
Please Credit Ontario Hydro Research if
Reproduced in Whole or in Part

ontario hydro
research division

To: Mr. J.E. Mitchell
Manager
Technical Services and Development
Program Support and Services Division

# HARMONIC MEASUREMENTS AT LASCO - VARIABLE SPEED DRIVES

G.K. Hatanaka

Harmonic measurements were performed at Lake Ontario Steel Company (LASCO). Harmonic voltage measurements were performed on four different individual variable speed drives, two dc and two ac, and on the Bar Mill T13 bus. The total harmonic distortion (THD) on the T13 bus was 3.0% or less. This meets the 5% limit recommended by IEEE Std 519-1981 for a general, medium voltage power system.

## 1.0 *Introduction*

Lake Ontario Steel Company (LASCO) was experiencing some equipment problems, with motor drives tripping out in the Bar Mill section. LASCO resolved the problems, apparently associated with low bus voltage, by increasing the transformer taps. These problems, however, raised LASCO awareness of the possible impact of the harmonics generated by the large number of variable speed drives in the Bar Mill section on the proper operation and maintenance of plant equipment. LASCO raised these concerns with the Electrical Research Department. Research Division agreed to assess the severity of the harmonic conditions in the Bar Mill section. Measurements were made on the T13 bus under normal operating conditions to obtain the composite harmonic distortion. The results can be used to evaluate the need to take steps to avoid possible maloperation or damage to plant equipment. Additional measurements were taken on individual VSDs to validate a PC-based computer program being developed by Research staff, that allows a detailed harmonic analysis of VSDs. Details of the computer program and the program validation using the LASCO test results will be the subject of a separate report. This report describes the measurements as they apply to the LASCO concerns.

## 2.0 *Harmonic Distortion*

The voltage generated by a utility has a regular sinusoidal waveform and a steady peak or rms amplitude and frequency. However, at the point of utilization, excursions from this ideal are unavoidable.

Harmonics are additional sinusoidal waveforms whose frequencies are multiples (or submultiples in the case of ferroresonance and usually an integer) of the supply frequency (60 Hz).



| job | file | date | report no. |
|---|---|---|---|
| 18-140-112 | 816.22 | October 25, 1991 | 91-249-K |

## LEGAL NOTICE

This report was prepared by Ontario Hydro and, while effort has been made to assure the accuracy and applicability of the material contained herein, neither Ontario Hydro nor any person acting on its behalf:

(a) makes any warranty, express or implied with respect to the use of any information, apparatus, method or process disclosed in this report or that such use may not infringe privately owned rights; or

(b) assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method or process disclosed in this report.

Power electronic equipment such as variable speed ac/dc drives (VSDs), static power converters, battery chargers and uninterruptible power supplies (UPSs) are common sources of harmonics in industrial environments.

Phase-controlled, three-phase power converters also produce repetitive notches in the line-to-line voltage waveform during the commutation process when a brief short circuit is produced as the load is switched among the thyristor pairs to convert three phase ac to dc. The line commutation notches excite the natural resonance of the power system and appear as damped oscillatory transients.

Under normal conditions a q-pulse converter generates characteristic harmonics given by:

$$h = kq \pm 1$$

where h is the order of the harmonics
k = an integer, 1,2,3....and
q = the number of pulses.

The pulse number is the number of times the load current is switched among thyristors during one cycle to convert three phase ac to dc.

For example, a 6-pulse converter generates harmonics of order 5,7 and 11,13 and 17,19 etc. Other non-characteristic harmonics can be generated under abnormal operation or unbalances in the circuits but are typically lower in magnitude.

For the simple case of an uncontrolled rectifier with a constant dc output current, the input ac current is a square wave and the maximum magnitude of the harmonic currents is theoretically equal to the inverse of the harmonic order or 1/h. For example the $5^{th}$ harmonic current would be 1/5 or 20% of the fundamental. In practice the magnitudes will be less. A more detailed description of these harmonic characteristics can be found in the literature [1].

These harmonic currents flow into the power system and produce corresponding harmonic voltages due to the voltage drops across the system impedances. Because the system impedance is generally low, the resulting voltage harmonics have relatively low magnitudes and resulting composite voltage waveform is distorted much less than the current waveform.

VSDs can be considered as both a producer of disturbances and as a victim of disturbances:

> As a producer of disturbances, VSDs generate harmonics and line voltage notches that can disturb equipment on the same load distribution system and the utility supply system.
>
> As a victim of disturbances, VSDs may be susceptible to harmonics and line voltage notches, as well as other types of power line disturbances such as voltage sags and swells and transient surges that may be present on the incoming supply.

Research Division report no 90-302-K [3] describes both aspects of VSD performance and reviews common design practices for minimizing the effects.

## 3.0 *Description of Tests*

Figure 1 shows a simplified single line diagram of the LASCO Bar Mill. Harmonic measurements were performed on the composite waveform on the 4160 V, Bar Mill T13 bus. Tests were done with the Bar Mill both down and in operation. During operating conditions the Straightener was not running.

Harmonic measurements were also performed on the voltage waveforms associated with the operation of four different types of VSDs at the low voltage levels of either 600 V or 480 V. These measurements were done while the Mill was down. The drives were individually turned on for the tests. Two of the drives were dc and the other two were ac as follows:

1. Rotating Transfer - DC Motor Drive (250 hp).
2. Straightener - DC Motor Drive (400 hp).
3. Cooling Bed Runout - AC Motor Drive (125 hp).
4. Bar Mill Top Zone Combustion Fan - AC Motor Drive (470 hp).

The Rotating Transfer and the Straightener dc motor drives use a conventional 6-pulse, ac-to-dc converter. This consists of a line-commutated, 6-pulse thyristor bridge. The Cooling Bed Runout uses a standard ac motor drive which consists of an ac-to-dc converter, a dc-link filter, and a dc-to-ac inverter. The inverter is a conventional 6-step voltage source inverter (VSI), which requires a large capacitor in the dc-link filter. The Bar Mill Top Zone Combustion Fan ac motor drive uses a pulse-width modulated current-source-inverter (PWM-CSI). The front-end uses a diode bridge to convert ac to dc.

Harmonic measurements were performed using the HP3562A Dynamic Signal Analyzer. This analyzer can be used as a conventional two-channel FFT (Fast Fourier Transform) signal analyzer that stores frequency domain data or as a single-channel instrument in Time Capture mode to digitize and store the captured time domain waveform on a 3-1/2 inch floppy disk, which can be downloaded to the HP3562A for detailed post-measurement analysis.

Single-channel measurements of the phase voltage were done sequentially in the time capture mode with a frequency span of 5 kHz to provide a time domain waveform. External triggering was used (trigger on the same point of the voltage waveform) to provide a reference for phase angle information. FFT calculations on the time captured data were performed in a frequency span of 5 kHz, using the flat-top window. The flat-top window provides the best results for measurements of discrete spectral lines such as harmonics. The HP3562A automatically calculates the total harmonic distortion (THD) up to the 21st harmonic.

The HP3562A is a single-ended, low signal level instrument and appropriate signal conditioning is required for measurements on power circuits. A custom-made instrumentation transformer (600V/240V/120V:6 V) was used for connection to the 480 V and 600 V buses, and the 120 V secondary of the metering PT connected to the 4160 V, T13 bus.

## 4.0 *Distortion Criteria*

The most common criterion used to quantify the waveform distortion is the total harmonic distortion (THD) where the root-mean-square (rms) value of all the harmonics is expressed as a percentage of the fundamental.

For the voltage waveform this is defined as follows:

$$THD = \frac{\left(\sum_{h=2}^{H} V_h^2\right)^{1/2}}{V_1} \times 100\%$$

where $V_h$ is the harmonic rms voltage
$V_1$ is the fundamental rms voltage
h is the harmonic order, an integer and
H is the highest harmonic used.

Because harmonic voltages generally fall off quickly at the higher harmonic numbers, the lower order harmonics such as the 5th and 7th usually dominate the THD.

The current THD can be similarly defined. A lot of confusion is often created when the THD is used without specifying whether it refers to the voltage or current waveform.

The voltage THD is generally used as a figure of merit for the quality of the supply voltage. Ontario Hydro stipulates limits of voltage THD on the utility supply Distribution Electric System (DES)/2/. The Ontario Hydro requirements do not apply to the customer distribution supply system. IEEE Std 519-1981 /1/ recommends limits of acceptable voltage distortion on customer low-voltage systems (480 V) in addition to limits for medium and high voltage power systems. The Ontario Hydro requirements for the medium voltage DES are more stringent than the IEEE recommendations. These harmonic limits are summarized in Table 1.

**Table 1 Harmonic Limits**

| Where the Limits Apply | Voltage THD | | Applicable Standard |
|---|---|---|---|
| Utility Distribution Supply System | Dedicated Feeder[1] | 5% | Ontario Hydro Administrative Branch Procedure 2 |
| | General Feeder | 3% | |
| Medium Voltage Power System 2.4 - 69 kV | Dedicated System[2] | 8% | IEEE Standard 519-1981 |
| | General Power System | 5% | |
| High Voltage Power System 115 kV and above | Dedicated System[2] | 1.5% | |
| | General Power System | 1.5% | |
| Low Voltage System 460 V | Dedicated System[2] | 10% | |
| | General System | 5% | |

1. A dedicated feeder is one that feeds only one customer.
2. A dedicated system is one that services only converters or loads not affected by voltage distortion.

## 5.0 *Test Results*

Table 2 gives the composite harmonic distortion of the T13 bus voltage with the Bar Mill both down and operating. Table 3 characterizes the voltage distortion for the four different individual drives.

**Table 2 Total Harmonic Distortion of Voltage on LASCO T13, 4160 V Bus**

| Condition | $V_{r-w}$ | $V_{w-b}$ | $V_{b-r}$ |
|---|---|---|---|
| Mill Down | 0.6% | 0.7% | 0.6% |
| Mill Running† | 1.4% | 1.4% | 3.0% |
| † Straightener was not running | | | |

**Table 3 Total Harmonic Distortion from Individual VSDs at 600 V or 480 V System Voltage**

| Type of Drive | AC Input Voltage THD |
|---|---|
| Rotating Transfer | 8.3% |
| Straightener | 9.2% |
| Cooling Bed Runout | 4.2% |
| Bar Mill Top Zone Combustion Fan | 1.8%† |
| † Drive running at 40% of 800 A. | |

Figures 2 to 7 show the measured voltage waveforms and the corresponding harmonic content of the ac input line voltage for the different tests. Tables 4 to 9 list the corresponding individual harmonic magnitudes and phase angles.

The voltage distortion on the 4160 V bus is clearly higher when the Bar Mill is in operation. Nevertheless, under the measured conditions the distortion is within the recommended limits of IEEE-519 for a medium voltage power system. The voltage distortion is higher on the low-voltage buses (480 V and 600 V) with the individual drives in operation. This higher distortion results from the additional impedance of the 4160 V/480 V or 4160 V/600 V step-down transformers.

All drives use a standard six-pulse converter at the front-end. Therefore, the ac line inputs have the same characteristic harmonics, ie 5,7 and 11, 13 etc. The magnitudes of the voltage harmonics differ depending on the load current and the source impedance at the point of connection. The source impedance for each drive is dominated by the leakage impedance of the utility distribution supply transformer (44kV/4160V) and the 4160V distribution step down transformer (4160V/480V or 4160V/600V) feeding each drive.

Commutation notches are very evident in both dc drive waveforms. These notches are missing in the Cooling Bed Runout motor drive voltage waveform because the thyristors are in full conduction (0° firing angle). The Top Zone Combustion Fan motor drive waveform also has no notches because it uses a diode bridge converter.

## 6.0 *Conclusion*

The harmonic conditions on the 4160 V, T13 bus in the LASCO Bar Mill are not excessive. The total harmonic distortion is within the IEEE recommended limit for a medium voltage power system.


## 7.0 *Acknowledgements*

I wish to thank Scot Hutchinson, Steve D'Aguire and Tom McCrory of LASCO for their cooperation and assistance in conducting the tests. I am also grateful to Richard Cheung of Ryerson, Bruno Pietrantonio and Don Wisenden for their fine work throughout the project.


Approved:

A.F. Baljet
Manager
Electrical Research Department

Submitted

Glenn Hatanaka
Research Engineer
System Studies Section

## *References*


[1] IEEE Std 519-1981, "IEEE Guide for Harmonic Control and Reactive Compensation of Static Power Converters."

[2] Ontario Hydro Regions Branch Administrative Procedure 2, "Controlling Propagation of Harmonics into the DES by Customers," OOOH, Ser. 2.6, Sec. 6.3, September 1983.

[3] G.K. Hatanaka, "Power Quality Aspects of Variable Speed Drives", Research Report No. 90-302-K, December 18, 1990.

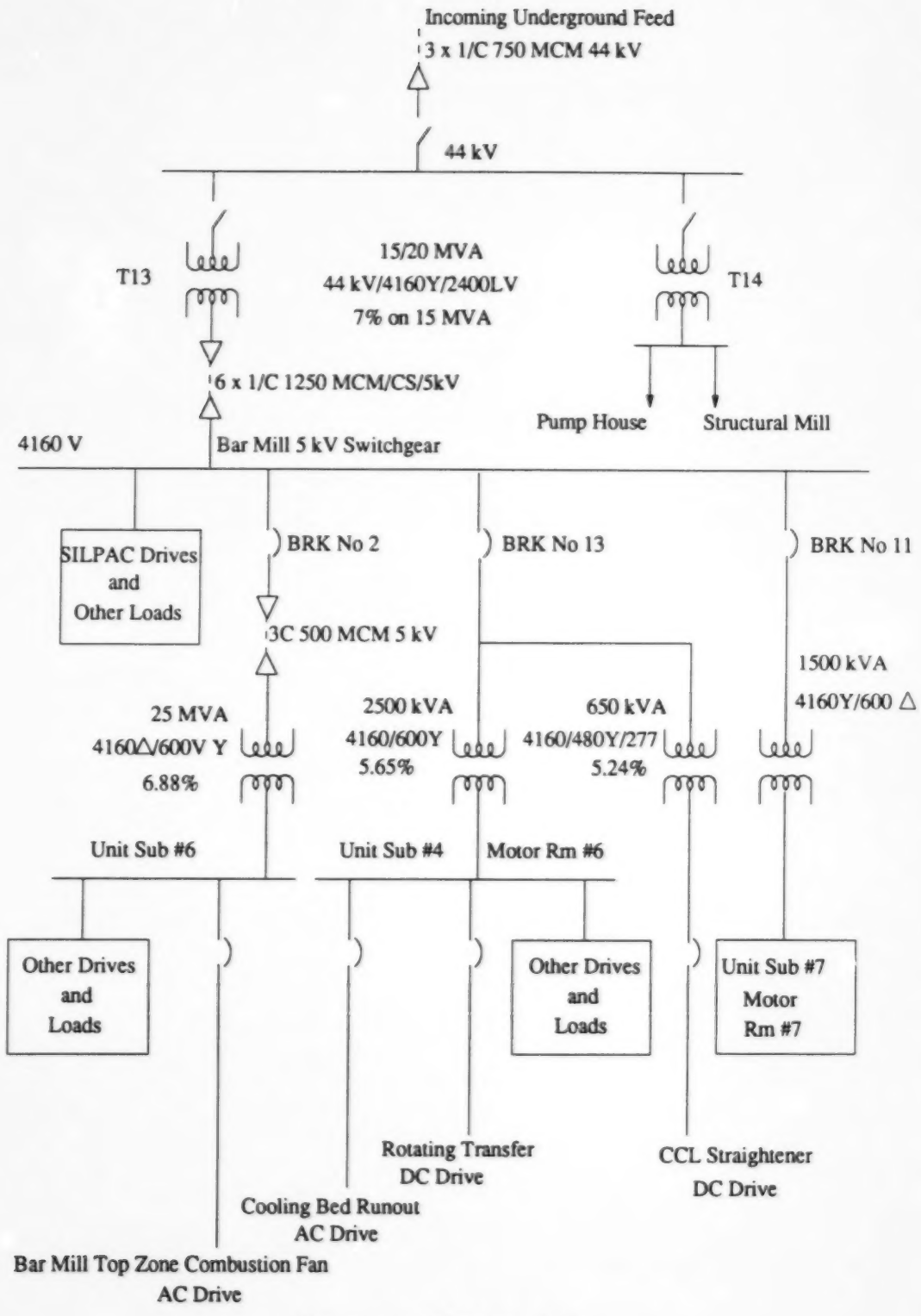


**Figure 1 LASCO Bar Mill**

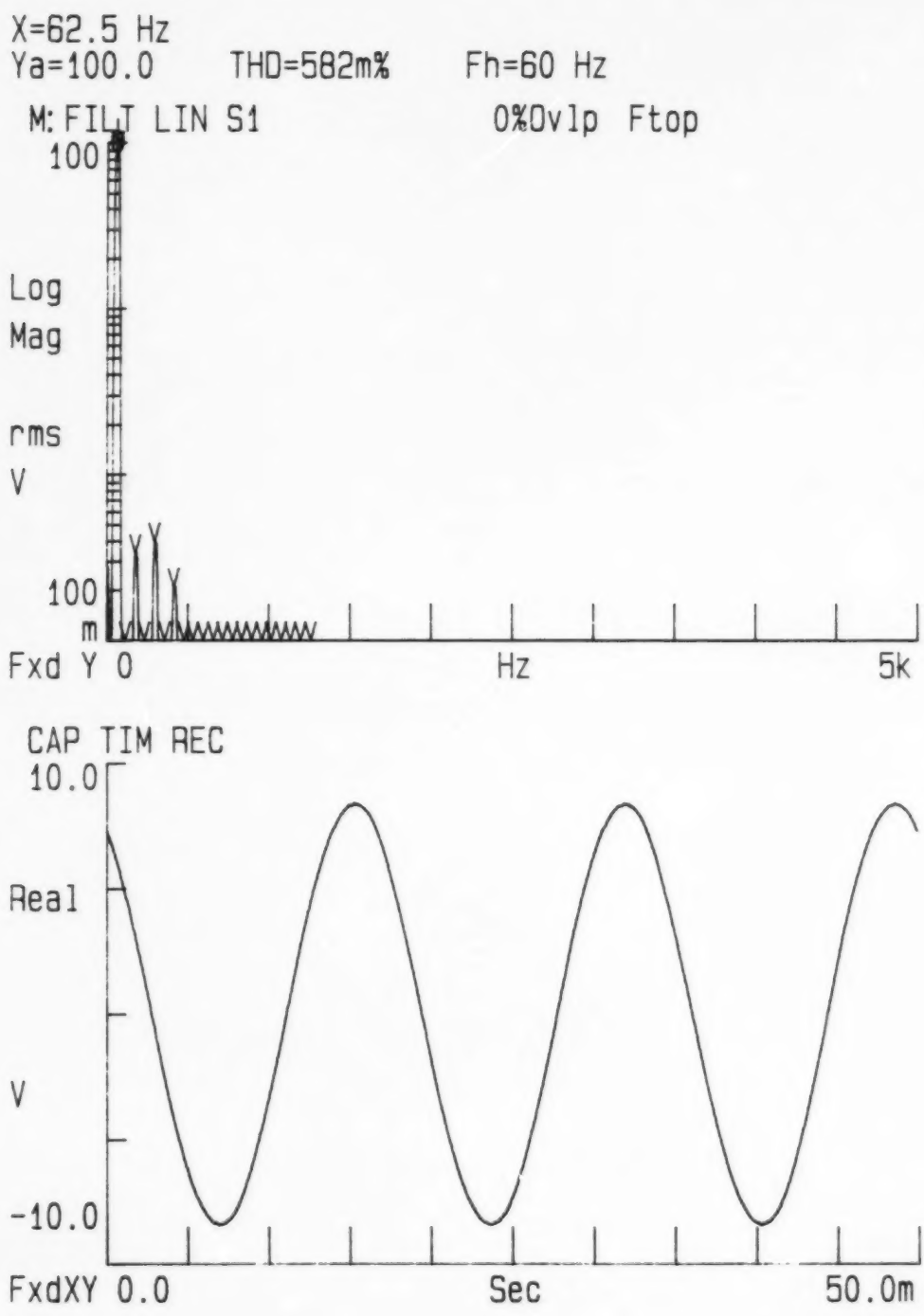


**Figure 2 LASCO Bar Mill (T13, 4160 V Bus), Mill Not Running.**

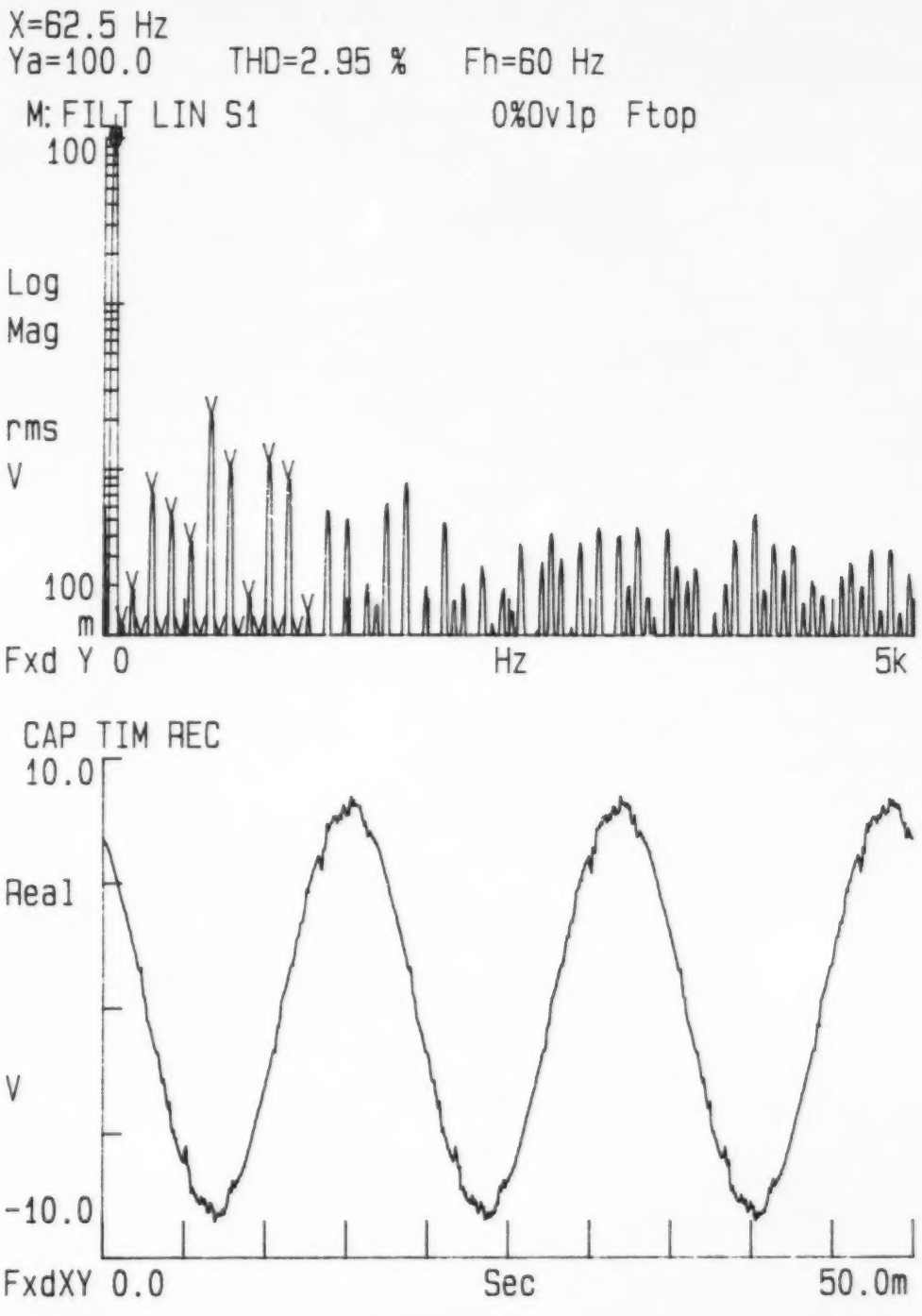


**Figure 3 LASCO Bar Mill (T13, 4160 V Bus), Mill Running.**

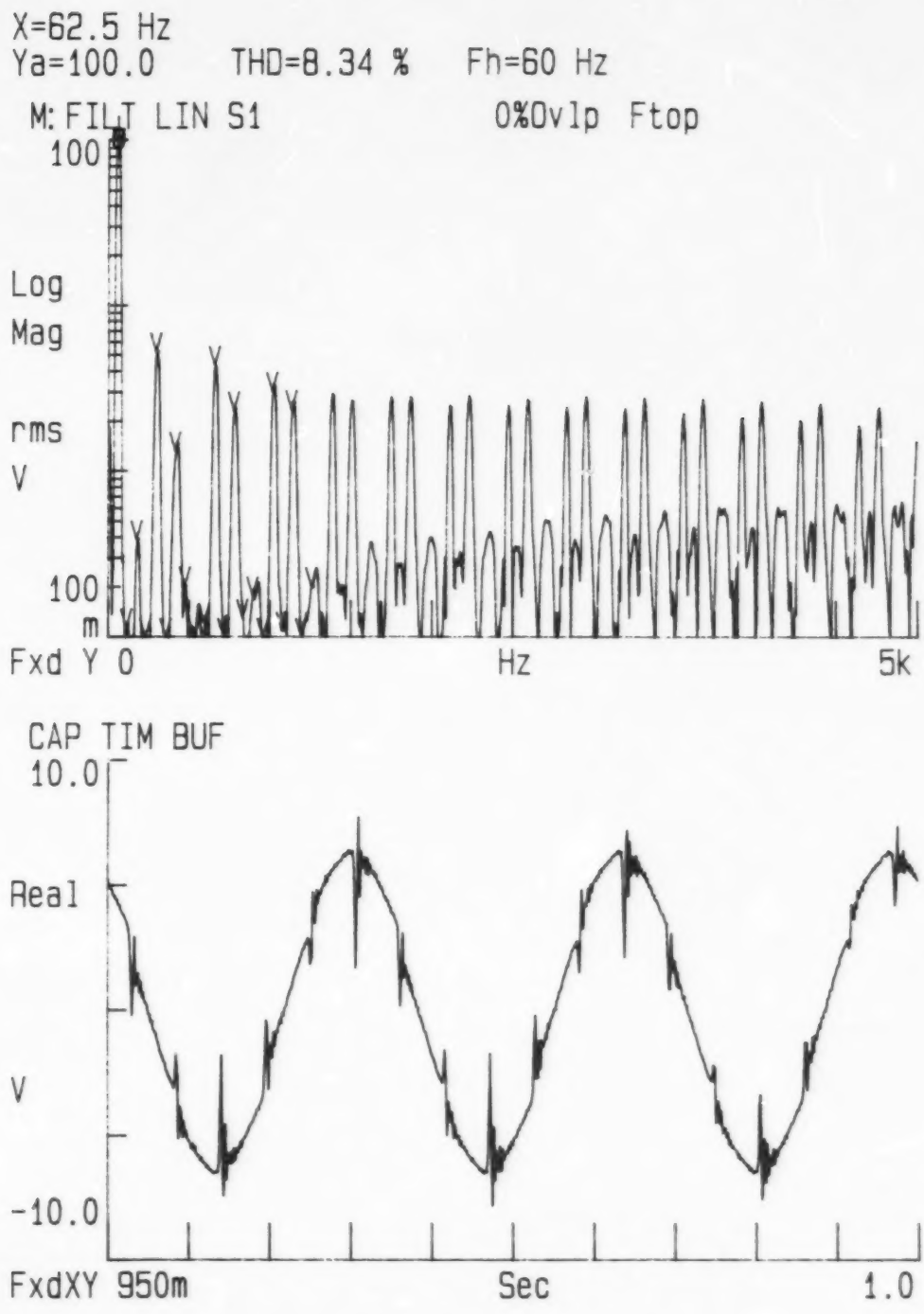


**Figure 4** **Rotating Transfer: 6-Pulse Converter, DC Motor Drive.**

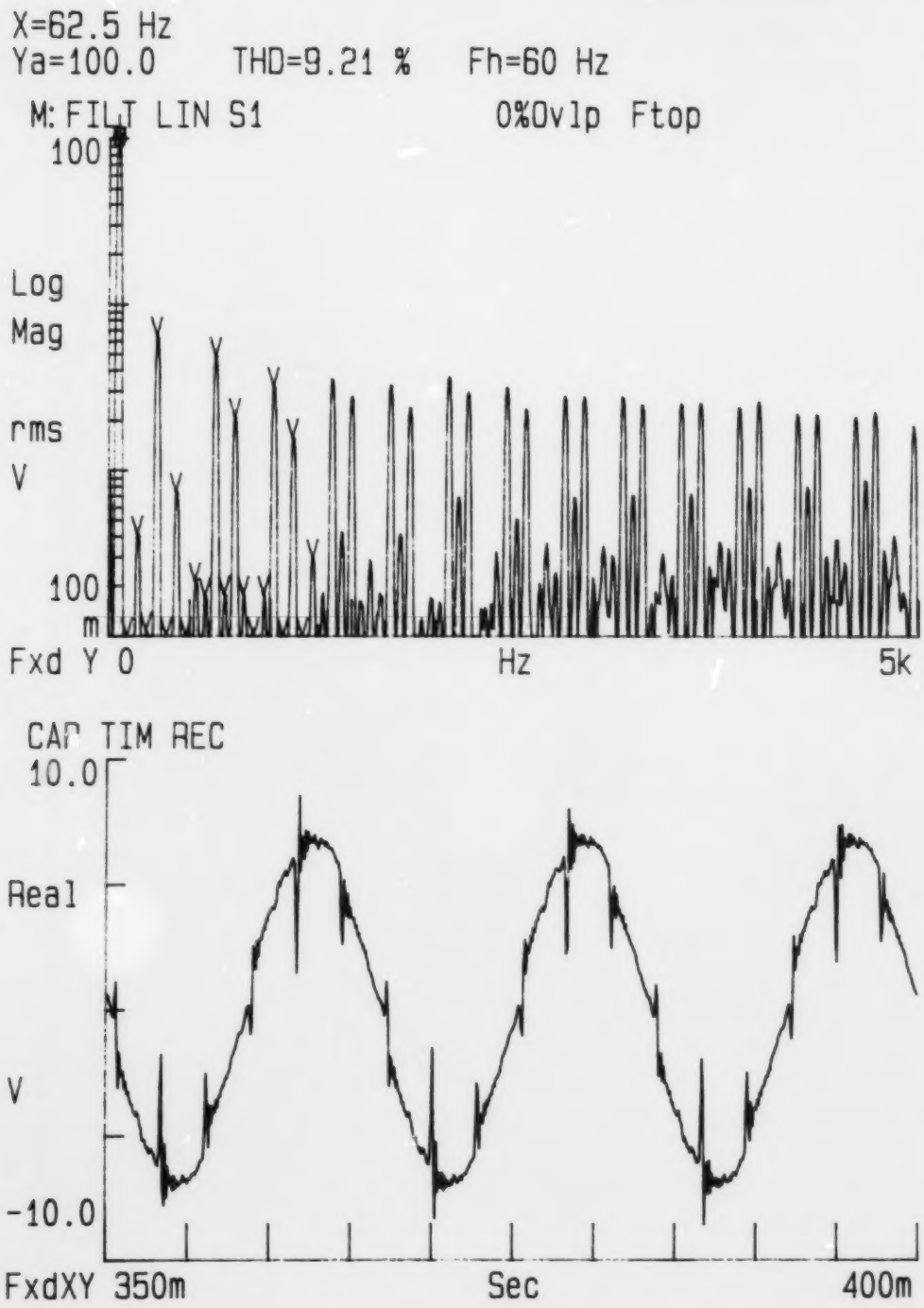


**Figure 5** **Straightener: 6-Pulse Converter, DC Motor Drive.**

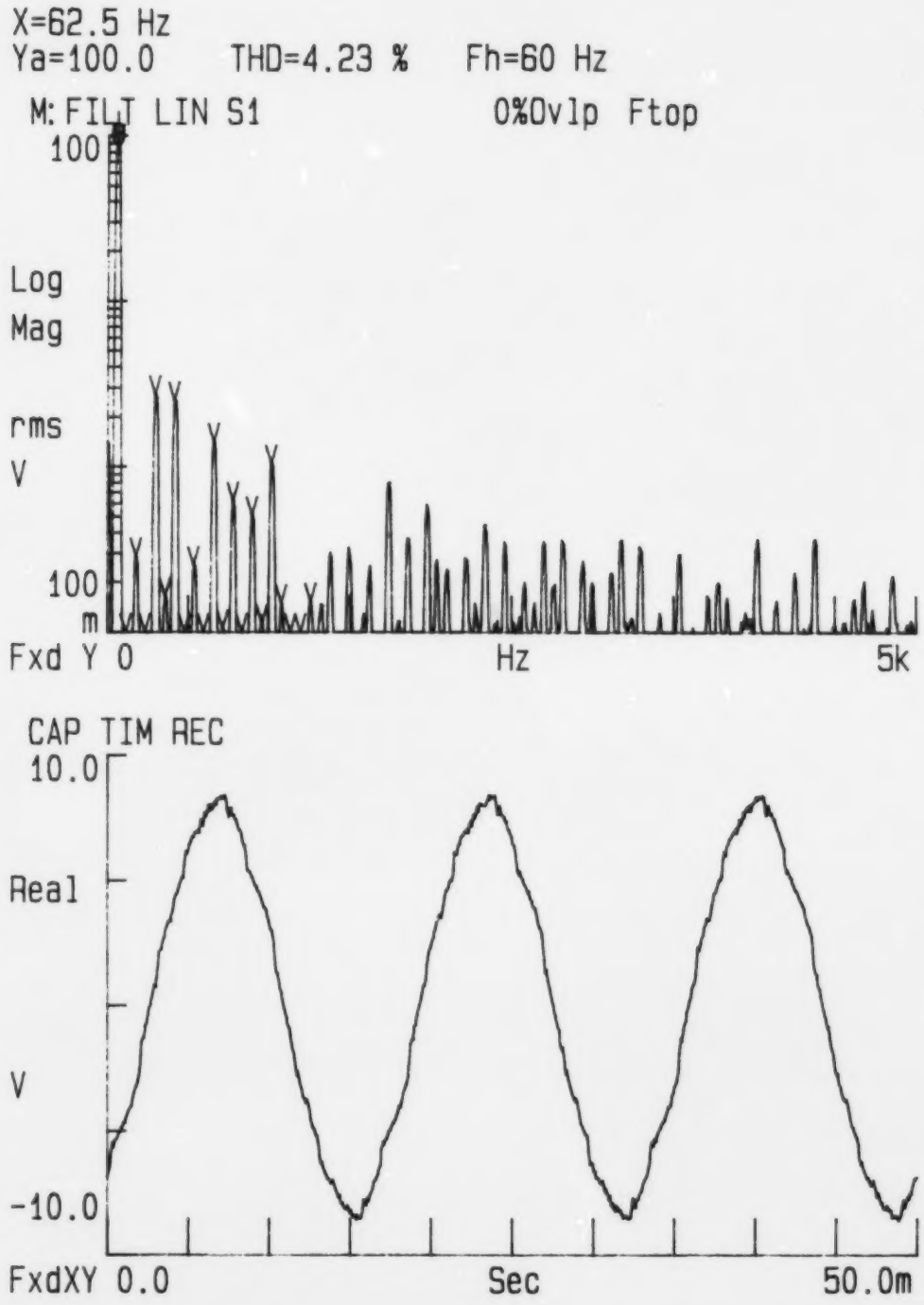


**Figure 6** **Cooling Bed Runout: Voltage-Source-Inverter (VSI), AC Motor Drive.**

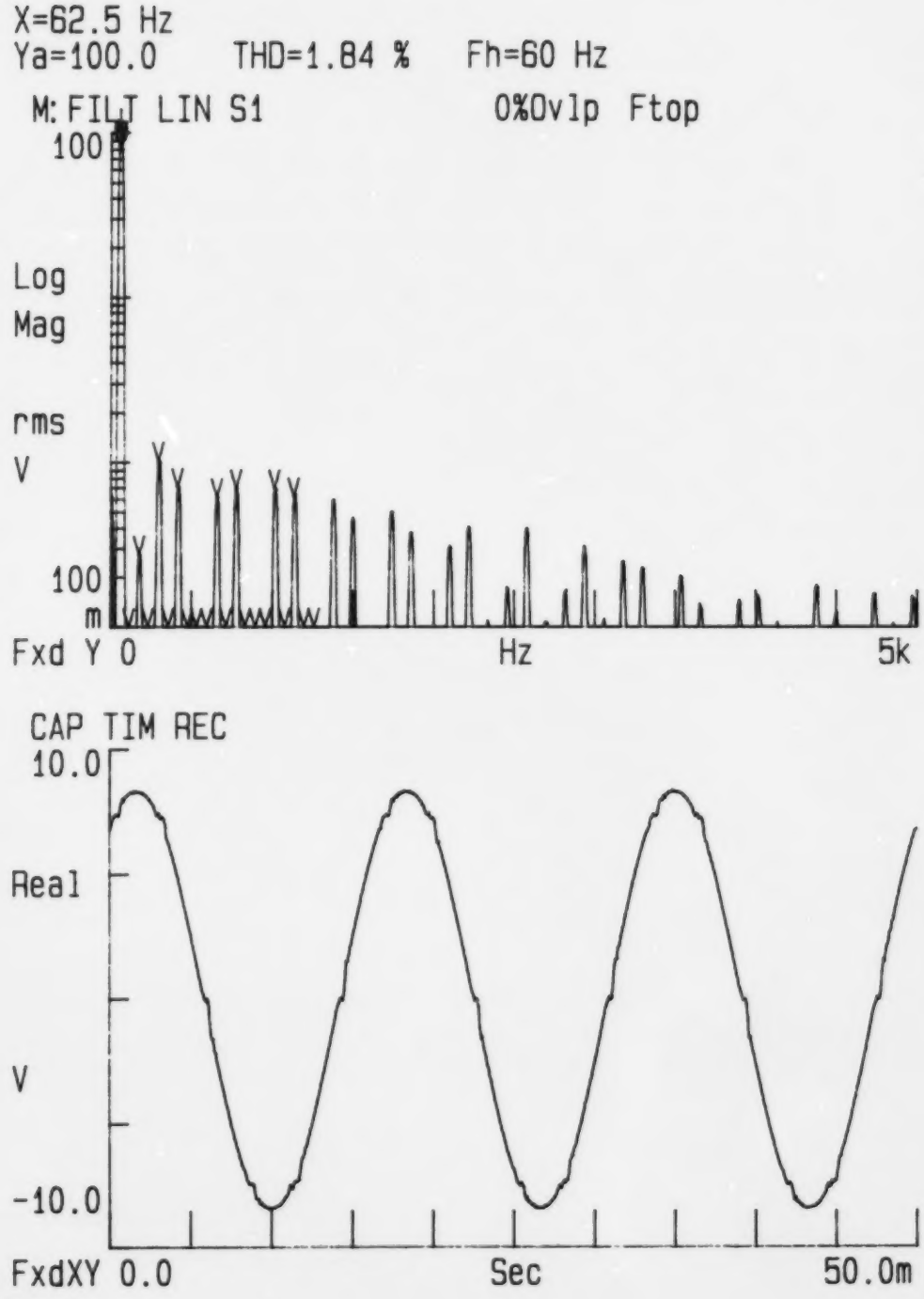


**Figure 7** **Bar Mill Top Zone Combustion Fan: Pulse-Width-Modulated Current-Source-Inverter (PWM-CSI), AC Motor Drive.**

**Table 4 LASCO Bar Mill (T13, 4160 V Bus), Mill Not Running.**

Filename: T13_6
Vb-r : Fund 117.07V rms Composite 117.07V rms
THD= .6 %

| Harmonic number | Frequency Hz | Magnitude % of fund. | Phase degrees |
|---|---|---|---|
| 1 | 60 | 100.00 | -37 |
| 2 | 120 | .01 | 10 |
| 3 | 180 | .34 | 150 |
| 4 | 240 | 0.00 | 0 |
| 5 | 300 | .39 | 96 |
| 6 | 360 | .02 | -14 |
| 7 | 420 | .22 | -99 |
| 8 | 480 | .02 | 131 |
| 9 | 540 | .01 | 46 |
| 10 | 600 | 0.00 | 0 |
| 11 | 660 | .08 | -15 |
| 12 | 720 | 0.00 | 0 |
| 13 | 780 | .05 | -10 |
| 14 | 840 | 0.00 | 0 |
| 15 | 900 | .03 | -77 |
| 16 | 960 | 0.00 | 0 |
| 17 | 1020 | .03 | 132 |
| 18 | 1080 | .01 | -178 |
| 19 | 1140 | .08 | -75 |
| 20 | 1200 | .01 | 13 |
| 21 | 1260 | .01 | 108 |

**Table 5 LASCO Bar Mill (T13, 4160 V Bus), Mill Running.**

Filename: TIME6
Vb-r : Fund 112.36V rms Composite 112.41V rms
THD= 3.0 %

| Harmonic number | Frequency Hz | Magnitude % of fund. | Phase degrees |
|---|---|---|---|
| 1 | 60 | 100.00 | -35 |
| 2 | 120 | .12 | 72 |
| 3 | 180 | .19 | -167 |
| 4 | 240 | .02 | 137 |
| 5 | 300 | .74 | 169 |
| 6 | 360 | .01 | -149 |
| 7 | 420 | .53 | 103 |
| 8 | 480 | .06 | 147 |
| 9 | 540 | .37 | 61 |
| 10 | 600 | .05 | 60 |
| 11 | 660 | 2.14 | -147 |
| 12 | 720 | .06 | -45 |
| 13 | 780 | 1.02 | -166 |
| 14 | 840 | .08 | 120 |
| 15 | 900 | .17 | 122 |
| 16 | 960 | .08 | 172 |
| 17 | 1020 | 1.12 | -161 |
| 18 | 1080 | .04 | -20 |
| 19 | 1140 | .87 | -150 |
| 20 | 1200 | .05 | 121 |
| 21 | 1260 | .14 | 121 |

**Table 6 Rotating Transfer: 6-Pulse Converter, DC Motor Drive.**

Filename: 3
Vr-w : Fund 427.21V rms Composite 428.70V rms
THD= 8.3 %

| Harmonic number | Frequency Hz | Magnitude % of fund. | Phase degrees |
|---|---|---|---|
| 1 | 60 | 100.00 | 126 |
| 2 | 120 | .09 | -125 |
| 3 | 180 | .25 | -45 |
| 4 | 240 | .02 | -43 |
| 5 | 300 | 5.36 | 54 |
| 6 | 360 | .04 | 143 |
| 7 | 420 | 1.40 | -82 |
| 8 | 480 | .08 | 47 |
| 9 | 540 | .07 | -120 |
| 10 | 600 | .16 | 165 |
| 11 | 660 | 4.21 | 58 |
| 12 | 720 | .10 | 106 |
| 13 | 780 | 2.23 | -64 |
| 14 | 840 | .08 | -31 |
| 15 | 900 | .05 | 128 |
| 16 | 960 | .06 | -154 |
| 17 | 1020 | 3.38 | 73 |
| 18 | 1080 | .14 | 123 |
| 19 | 1140 | 2.16 | -59 |
| 20 | 1200 | .10 | 78 |
| 21 | 1260 | .10 | -172 |

**Table 7 Straightener: 6-Pulse Converter, DC Motor Drive.**

Filename: 11
Vr-w : Fund 463.09V rms Composite 465.06V rms
THD= 9.2 %

| Harmonic number | Frequency Hz | Magnitude % of fund. | Phase degrees |
|---|---|---|---|
| 1 | 60 | 100.00 | 19 |
| 2 | 120 | .08 | -136 |
| 3 | 180 | .35 | 59 |
| 4 | 240 | .03 | 65 |
| 5 | 300 | 6.51 | 18 |
| 6 | 360 | .04 | 154 |
| 7 | 420 | .63 | 97 |
| 8 | 480 | .09 | 27 |
| 9 | 540 | .17 | 19 |
| 10 | 600 | .09 | -46 |
| 11 | 660 | 5.01 | -102 |
| 12 | 720 | .12 | 41 |
| 13 | 780 | 2.10 | -15 |
| 14 | 840 | .16 | -23 |
| 15 | 900 | .06 | -58 |
| 16 | 960 | .09 | 172 |
| 17 | 1020 | 3.21 | 140 |
| 18 | 1080 | .01 | 2 |
| 19 | 1140 | 1.51 | -160 |
| 20 | 1200 | .08 | 169 |
| 21 | 1260 | .30 | 177 |

**Table 8** **Cooling Bed Runout: Voltage-Source-Inverter (VSI), AC Motor Drive.**

Filename: 3
Vr-w : Fund 565.35V rms Composite 565.86V rms
THD= 4.2 %

| Harmonic number | Frequency Hz | Magnitude % of fund. | Phase degrees |
|---|---|---|---|
| 1 | 60 | 100.00 | 146 |
| 2 | 120 | .05 | -120 |
| 3 | 180 | .29 | 46 |
| 4 | 240 | .09 | 62 |
| 5 | 300 | 2.74 | 3 |
| 6 | 360 | .17 | -82 |
| 7 | 420 | 2.52 | -175 |
| 8 | 480 | .04 | -108 |
| 9 | 540 | .25 | -37 |
| 10 | 600 | .06 | 92 |
| 11 | 660 | 1.42 | -170 |
| 12 | 720 | .11 | -116 |
| 13 | 780 | .62 | -61 |
| 14 | 840 | .06 | -115 |
| 15 | 900 | .51 | -38 |
| 16 | 960 | .11 | -69 |
| 17 | 1020 | 1.05 | 179 |
| 18 | 1080 | .15 | 37 |
| 19 | 1140 | .08 | -134 |
| 20 | 1200 | .11 | 112 |
| 21 | 1260 | .15 | 155 |

**Table 9** **Bar Mill Top Zone Combustion Fan: Pulse-Width-Modulated Current-Source-Inverter (PWM-CSI), AC Motor Drive.**

Filename: 3
Vr-w : Fund 588.37V rms Composite 588.47V rms
THD= 1.8 %

| Harmonic number | Frequency Hz | Magnitude % of fund. | Phase degrees |
|---|---|---|---|
| 1 | 60 | 100.00 | -103 |
| 2 | 120 | .03 | -4 |
| 3 | 180 | .28 | -163 |
| 4 | 240 | .02 | 84 |
| 5 | 300 | 1.02 | 50 |
| 6 | 360 | .02 | -104 |
| 7 | 420 | .71 | 55 |
| 8 | 480 | .02 | -76 |
| 9 | 540 | .09 | 151 |
| 10 | 600 | .01 | -129 |
| 11 | 660 | .62 | -28 |
| 12 | 720 | .01 | 61 |
| 13 | 780 | .70 | -44 |
| 14 | 840 | .01 | 71 |
| 15 | 900 | .06 | 41 |
| 16 | 960 | .01 | -8 |
| 17 | 1020 | .70 | -133 |
| 18 | 1080 | .02 | -61 |
| 19 | 1140 | .63 | -144 |
| 20 | 1200 | .01 | 103 |
| 21 | 1260 | .09 | -92 |